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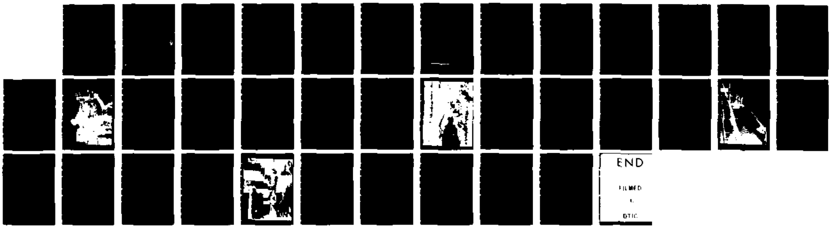

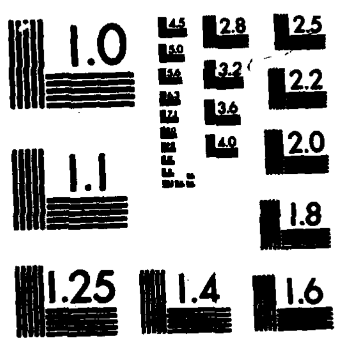

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Defense Mapping Agency (DMA) performs major geodetic and geophysical surveys to support the mapping, charting, and geodesy requirements of the Department of Defense. These survey requirements are often at the edge of the state-of-the-art and require extensive DMA involvement in the development and testing of new survey methodology.

This paper covers the results of recent test and evaluation programs involving prototype and state-of-the-art production instrumentation for astronomic

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position and azimuth determinations, multi wavelength distance measurements, and improvements in gravity measurements. The treatment of principal error sources in astronomic positioning through the use of the recently developed charge coupled device eyepiece to eliminate personal equation bias, the investigation of precise astrolabes, the establishment of precise astronomic reference stations, and the status of current research for the development of a two color refractometer to correct for anomalous atmospheric refraction are discussed. Also covered are the acceptance tests and future plans for the improvement of distance measurement (Terrameter). Brief discussions of DMA's participation in programs to improve the U. S. Gravity Base Network, the acquisition, reduction, and adjustment of relative gravity surveys, and support to the field testing of an absolute gravity apparatus are included.

Developmental Efforts to Improve the Accuracies of Geodetic and Geophysical Surveys

by

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ABSTRACT

The Defense Mapping Agency (DMA) performs major geodetic and geophysical surveys to support the mapping, charting, and geodesy requirements of the Department of Defense. These survey requirements are often at the edge of the state-of-the-art and require extensive DMA involvement in the development and testing of new survey methodology.

This paper covers the results of recent test and evaluation programs involving prototype and state-of-the-art production instrumentation for astronomic position and azimuth determinations, multiwavelength distance measurements, and improvements in gravity measurements. The treatment of principal error sources in astronomic positioning through the use of the recently developed charge-coupled device eyepiece to eliminate personal equation bias, the investigation of precise astrolabes, the establishment of precise astronomic reference stations, and the status of current research for the development of a two-color refractometer to correct for anomalous atmospheric refraction are discussed. Also covered are the acceptance tests and future plans for the improvement of distance measurement (Terrameter). Brief discussions of DMA's participation in programs to improve the U. S. Gravity Base Network, the acquisition, reduction, and adjustment of relative gravity surveys, and support to the field testing of an absolute gravity apparatus are included.

Development Efforts to Improve the Accuracies of Geodetic and Geophysical Surveys

In 1972, the separate geodetic survey resources of the Army, Navy, and Air Force were consolidated into one agency. The Defense Mapping Agency (DMA), in Washington, D. C. , is responsible for all geodetic and geophysical surveys that are necessary to support Department of Defense programs. This agency includes the Hydrographic/Topographic Center (DMAHTC) and Office of Distribution Services, located in Washington, D.C.; the Defense Mapping School, at Fort Belvoir, Virginia; the Aerospace Center, in St. Louis, Missouri; and headquarters of the Inter American Geodetic Survey, at Fort Sam Houston, Texas. delete

The DMAHTC Geodetic Survey Squadron (DMAHTC/GSS), at F. E. Warren Air Force Base in Cheyenne, Wyoming, is the location where most of DMA's geodetic survey resources were consolidated in late 1976 under the Geodesy and Surveys Department of the DMAHTC. This organization is engaged in geodetic and geophysical surveying worldwide. There are permanent detachments of geodetic survey personnel at Vandenberg Air Force Base, California; White Sands Test Range and Holloman Air Force Base, New Mexico; and Patrick Air Force Base, Florida, providing survey support to these national test ranges. delete

Ultraprecise surveys are needed to support the testing of advanced aerospace technology, which includes the orientation and calibration of inertial guidance systems, improved measurements of relative and absolute gravity, accurate determinations of the deflection of the vertical, accuracy improvements approaching 10^{-7} in distance measurements, support to the development of improved national geodetic control land gravity base networks, and refinements of the world geodetic system.

It is with this background in mind that we will review DMA's development efforts over the past 5 years in geodetic and gravity surveys. Emphasis will be on the role of the DMAHTC Geodetic Survey Squadron in completing operational testing and evaluation of new survey instrumentation under field conditions, modifications of instruments and procedures to improve accuracies, and contributions to improved gravity base networks. In many cases, these developments have involved the collaborative efforts of other U.S. government agencies and universities.

DEFLECTIONS OF THE VERTICAL

During the last decade, DMA recognized the urgent need to improve survey capabilities for determining deflections of the vertical. Studies were made of astrogeodetic determinations, inertial positioning system (IPS) measurements, gravimetric determinations, and interpolation/prediction by least-squares collocation methods. The results of these studies, and other practical considerations, indicated that the most cost effective approaches would be improving the accuracies of astronomic position determinations.

An in-house investigation of the error sources affecting astronomic observations was initiated. In order to provide a reference for future improvements and the identification of error sources, a capability study was undertaken between August and November 1977 by the Geodetic Survey Squadron.

The purpose was to determine the best attainable accuracy of conventional astronomic position observations using DMA-qualified astro observers, standard equipment, and currrent observing methodology. This study involved 14 observers using Wild T-4 astronomic theodolites at a standard station in Cheyenne, Wyoming. The meridian transit method was used for longitude and the Sterneck method for latitude. The results were published in 1979 (Gilbert, 1979).

This capability study provided a rational basis for isolating and analyzing the most important error sources in astronomic position determinations. The results of these tests were substantiated by reviewing the literature of research and instrument tests that had been performed in Europe.

The means of the 338 sets of latitude determinations and 322 sets of longitude determinations in the Cheyenne test by 14 observers were accepted as the true astronomic position of the standard station. It was assumed that the personal equation, instrument bias, and anomalous refraction would cancel over an extended period of time with the different observers using different instruments. This assumption was proven substantially correct. The findings of the test were that the estimated accuracies of DMA astronomic stations are as follows:

Table 1

	LATITUDE	LONGITUDE
First Order (2 nights)	±0.″15	±0.″25 secant ϕ
Modified First Order (1 night)	±0.″19	±0.″28 secant ϕ

Other findings were:

- No significant observer's personal equation was found in the astronomic latitude data samples.

- Thirteen of the fourteen observers had significant personal equations in astronomic longitude data samples.

- Personal equations of the observers ranged from 0.46 to 0.31 arc second.

Table 2 shows the combination of instruments, observers, and number of nights required to achieve improved astronomic position accuracies in latitude and longitude. The data indicate that almost double the effort is required to improve accuracy in longitude than is required in latitude. The reason is the large contribution of the personal equation error in longitude, which is not a significant factor in latitude. These findings provided the rationale that future improvement efforts be concentrated on longitude observations, which would undoubtedly improve the accuracy in latitude observations, [redacted]

A technical development program was formulated based on the significant findings of the Cheyenne capability study and a review of the research and development efforts of other studies performed in the international geodetic community. The comparison of astronomic position determinations using the

Table 2

STATISTICS OF ENHANCEMENT WITH VARIOUS COMBINATIONS OF INSTRUMENTS, PERSONNEL, AND OBSERVATIONS[1]

Astronomic Latitude Accuracy Improvement

No. of Instruments	No. of Observers	No. of Nights	Avg. No. of Sets	Avg. No. of Stars	Accuracy Std. Error	No. of Determinations
1	1	1	4	32	±0".19(MFO)	78
1	1	2	9	68	±0".15(FO)	38
1	2	3	11	84	±0".13	29
2	2	3	11	84	±0".15	28
2	2	5 to 7	22	170	±0".09	13

Astronomic Longitude Accuracy Improvement

No. of Instruments	No. of Observers	No. of Nights	Avg. No. of Sets	Avg. No. of Stars	Accuracy Standard Error	No. of Determinations
1	1	1	4	32	±0".28 sec ϕ (MFO)	78
1	1	2 to 4	8	69	±0".25 sec ϕ (FO)	37
1	2	3	11	86	±0".21 sec ϕ	25
1	3	3 to 4	11	91	±0".18 sec ϕ	26
2	2	2 to 3	8	66	±0".18 sec ϕ	34
2	2	5 to 6	18	151	±0".14 sec ϕ	13
1	1	2 to 4	8	69	±0".15 sec ϕ (FO)*	37

*After applying corrections for personal equations

[1]Gilbert, 1979, p.51

Danjon and the VUGTK astrolables published by the German Geodetic Commission (Kaniuth, Wende, and Schlüter, 1979) was significant. These tests, covering 18 months, were made principally for polar motion studies. The results of these tests indicated that astrolabes were capable of precision and accuracy surpassing astronomic theodolites, even though some personal equation bias still remained. This was not unexpected, since the Danjon precise astrolabe has been used by the U.S. Naval Observatory Timing Service for many years. Nevertheless, the German Geodetic Commission report reinforced the opinions at DMA that, in addition to improved instrumentation, precise astronomic reference stations linked to the U.S. Naval Observatory Timing Station in Washington, D.C., were needed at strategic locations throughout the U.S.

The technical development program, initiated by the DMAHTC/GSS, coincided with a decision by HQ DMA to fund a research program by the University of Maryland to develop a charge-coupled device (CCD) eyepiece for astronomic theodolites and a two-color refractometer. The charge-coupled device would eliminate a major source of error by replacing the human eye. The two-color refractometer, if successful, would provide a correction for anomalous refraction. These research contracts were negotiated by DMA in 1976. The research and development (R&D) program at the University of Maryland was directed by Dr. Douglas G. Currie, Department of Physics and Astronomy.

The major emphasis of the DMA in-house accuracy improvement program focused on three main categories of error in longitude determination and alternative solutions to remedy these error sources (Table 3). Also, the magnitude of the error contributed by each category was estimated.

1. Systematic Instrument Errors. Instrument errors are identified and defined in the following paragraphs.

a. Errors in Determination for Instrument Constants:

The constants to be determined for a Wild T-4 (or Kern DKM3A) theodolite include: (1) the mean width of the contact strips; (2) the lost motion of the impersonal micrometer; (3) the equatorial radius (the value of one revolution of the micrometer for a star in the equatorial plane); and (4) the level vial values of the vertical and hanging (striding) levels. Although calibrations can be done fairly accurately, the calibration constants do not remain stable. They change with time, temperature, spring tension, humidity, and mechanical wear, and require frequent recalibrations.

b. Errors Due to Thermal and Mechanical Flexure of the Telescope:

Thermal flexure of the telescope is caused by temperature differences in the parts of the telescope tube. For example, a 1°C increase will create lengthening of the heated side of a Wild T-4 telescope by 2.6 microns, causing a displacement of the objective lens by 8 arc seconds. For a Wild T-3 or Kern DKM3 theodolite, this error would be smaller (about 0.5 arc second (Hirsch, 1970)). The thermal flexure can be in any direction, whereas the mechanical flexure is generally in the zenith distance direction and is caused by the mass of the telescope (Schwebel, 1970). For a Wild T-4, the amount of the mechanical flexure is about 1 arc second times sin z; where z is the zenith distance of the telescope. The effect of the mechanical flexure can be eliminated by a modified method of latitude observations.

Table 3

MAJOR ERRORS IN LONGITUDE OBSERVATIONS

	INSTRUMENT BIAS	PERSONAL EQUATION (PE)	BETWEEN-NIGHT ERROR
CAUSES:			
	1. Level Vial	1. Judgment Error	1. Refraction Variations
	2. Width of Contact Strips	2. Magnitude of Stars	2. Temperature Gradients (in Levels & Instrument)
	3. Wobble	3. Physical & Emotional	3. Variations in Wobble
	4. Temperature Effects	4. Manipulation of Instrument	
	5. Lost Motion	5. Eye Adaptability	
ERROR	±0".12	±0".20	±0".13
REMEDIES:			
	Level Calibration (1)	Correction for PE (1,2)	Two-Color Refractometer (1)
	Measure Wobble (3)	Use of CCD System (1-5)	Insulation (2)
	Insulate Level Vials (1,4)	Multiple Observers (1-5)	Wind Protection (2)
	Make & Break Timing Contacts (2)	Astrolabes (1,2,4,5)	Wobble Determination (3)
	Multiple Instruments (1-5)	Motorized Micrometers (3,4)	New Observing Methods (1,3)
	Reference Stations (2,5)		Multiple Night Observations (1,2)
	Electronic Levels (1,4)		Astrolabes (2,3)
	Mercury Levels (1,4)		
	Astrolabes (5)		

c. Circle and Circle Index Errors:

Circle and circle index drifts are internal stresses caused by changes in ambient temperature, and are about 0.3 arc second per 1°C (Schwebel, 1970). This value was verified by an analysis of DMA observations at the standard station in White Sands ~~Test Range~~ Missile, New Mexico. Unbalanced observations and/or nonlinear temperature changes introduce systematic errors in position and azimuth observations.

d. Wobble and Roll Errors:

Wobble error is the erroneous position of the instantaneous trunnion axis (horizontal axis) in relation to the ideal position of the axis, especially in relation to the vertical axis of the theodolite. Wobble error affects the accuracy of longitude and azimuth observations. It is caused by imperfect trunnion axis support bearings, mechanical play, and imperfect roundness of the trunnion axis. It has been assumed that, by employing different instruments for the determination of astronomic data, the systematic error for any particular instrument would be canceled. This may not be true as will be seen later. Roll error, which has a similar effect on astronomic observations, is caused by a roll motion of the trunnion axis relative to the bearing system, and is due to unequal friction on the trunnion axis, unequal pressure on the bearings, and unequal elastic deformations and actual flattening of the bearings.

e. Temperature Gradients in Level Vials:

Thermal sensitivity of level vials and the uncertain reliability of measured values make the use of spirit levels undesirable. Level vials can change their sensitivity by as much as one percent per 1°C temperature change. Also, because the radius of curvature of a level vial is not constant throughout its length, the sensitivity of a vial changes with bubble length. Temperature gradients that exist between the ends of a vial cause a lateral shift of the bubble, resulting in an erroneous bubble center. Tests have shown that a temperature gradient of 0.01°C in a 150 millimeter long level vial, having a sensitivity of one arc second per 2 millimeter vial division, causes a shift of 0.1 arc second of the level bubble center (Schwebel, 1970). Attainable refinements in manufacturing level vials have nearly been reached. The systematic portion of level vial error results from the change of surface tension and fluid density of the level liquid caused by small temperature gradients inside the vial, impurities in the liquid, irregularities in the curvature of the inner vial surface, and inertial and hydrostatic forces. These errors are too unpredictable for accurate determinations. In order to reduce the effects of these error sources, vials are calibrated at different temperatures, bubble lengths are normally kept to one-half of vial length, and steps are taken to compensate for inclination errors by purposely unleveling the theodolite so that the algebraic sum of all inclination errors approaches, or becomes, zero. However, the systematic error introduced into astronomic data by temperature gradients in the level vials is a serious error that can

remain undetected. This error may be one of the principal causes of the night-to-night differences noted in the results of astronomic observations.

Investigations of instrument errors and solutions to the problem consumed considerable time and led to several interesting experiments. During the winter and spring of 1979-80, Dr. Lassi Kivioja of Purdue University investigated these problems at the DMAHTC/GSS. One experiment performed by Dr. Kivioja, using a Davidson autocollimator, was to test some of DMA's inventory of DKM-3 and Wild T-4 theodolites for trunnion axis roundness. A plane mirror was attached to the trunnion axis of the instrument, and readings were taken with the autocollimator for various vertical angles of elevation and depression. These collimator data were transferred to computer-drawn plots of each instrument's trunnion axis roundness. It was hoped that, for an individual instrument, corrections could be made for various angles of inclination. However, in subsequent calibrations, the roundness plot for an instrument's trunnion axis did not repeat satisfactorily. Also, for different T-4's or DKM-3's, the plots were not random enough to assume that "wobble error" would be completely canceled using different instruments.

Dr. Kivioja also experimented with different mercury containers with the idea of using mercury leveling to replace the spirit levels on the theodolites. Although these experiments led to some modifications of existing theodolites, particularly for azimuth determination, the overall results reinforced the premise that a precise astrolabe would be more suitable for astronomic position determination. The major advantages of mercury containers are (1) the fixed zenith distance overcoming trunnion axis errors; (2) mercury leveling, which is superior to spirit leveling; and (3) simplicity of design, which eliminates some mechanical instability problems aggravated by temperature changes. Also, it was felt that a precise astrolabe would be a more stable base instrument for both the charge-coupled device eyepiece and for the two-color refractometer modifications.

2. <u>Personal Equation</u>.

a. <u>Standard Reference Stations</u>:

The personal equation error is mainly a systematic error that cannot be determined accurately and usually does not remain constant. The variation in an observer's personal error can be minimized by experience, the gaining of confidence, by concentration, and being in good physical and emotional condition. For an experienced and capable observer, the tendency is for personal error to remain nearly constant for a "short period" of time. Without any modifications to the astronomic theodolite, personal errors can be reduced by following certain observational procedures. These procedures, used in some European countries, involve determining longitudes at reference stations before and after observations are made at field stations. The same instrument is used at both the reference and field stations. The longitude of a field station is then the sum of the longitudinal difference between the field and reference stations, and the longitude of the reference station. The reference stations, used for this purpose, must be connected to the national standard reference point. To verify the behavior of the personal equation, two or more observers must be employed. If highly accurate (superior first order) astronomic longitudes are required prior to, or in lieu of the development and availability of advanced astronomic instrument modifications

for production surveys, this method of observing astronomic longitude could be employed. It is a costly method, but high accuracy and reliability of the field station longitude value are achieved. Presently, three additional standard reference stations are being established for DMA by the U. S. Naval Observatory Time Service (NOTS) in Washington, D.C. At the NOTS Washington, D.C. station, Danjon astrolabe observations, spanning a period of 10 years, have been used to compute the astronomic latitude and longitude for that standard reference station. The three standard stations being established are located in Cheyenne, Wyoming; Lompoc, California; and the White Sands ~~Test~~ Missile Range, New Mexico. These reference stations will be used in the future for testing the charge-coupled device, two-color refractometer, and other advanced instrumentation. They can also be used to make precise longitude transfer determinations by utilizing the superior first-order conventional method mentioned above.

b. Charge-Coupled Device (CCD). The charge-coupled device uses a 3 x 4 millimeter silicon chip (semiconductor) which is highly sensitive to visible and near-infrared light. Incident light from a star enters the optics of the theodolite and is focused on the silicon chip creating an electron flow across 100 x 100 pixels in a rectangular grid. This flow of electrons, called charge coupling, can be moved to a point of detection, converted into an electronic signal that represents the star's position on the grid, and captured by the computer. The entire grid is scanned 40 times per second, but only a small portion, up to a 10 x 10 pixel patch, is stored on a computer magnetic tape. The software analyzes the small pixel patch, column by column, to detect the position of the star on the grid. A multiparameter curve fit of the signal determines when the star image enters and exits a grid column. From these curve fits, the grid position and time correlation of the star is determined. The rest of the data reduction process for latitude and longitude determination is analogous to conventional astronomic position data reduction procedures.

(1) CCD Hardware System. A schematic diagram of the CCD system is shown in Figure 1.

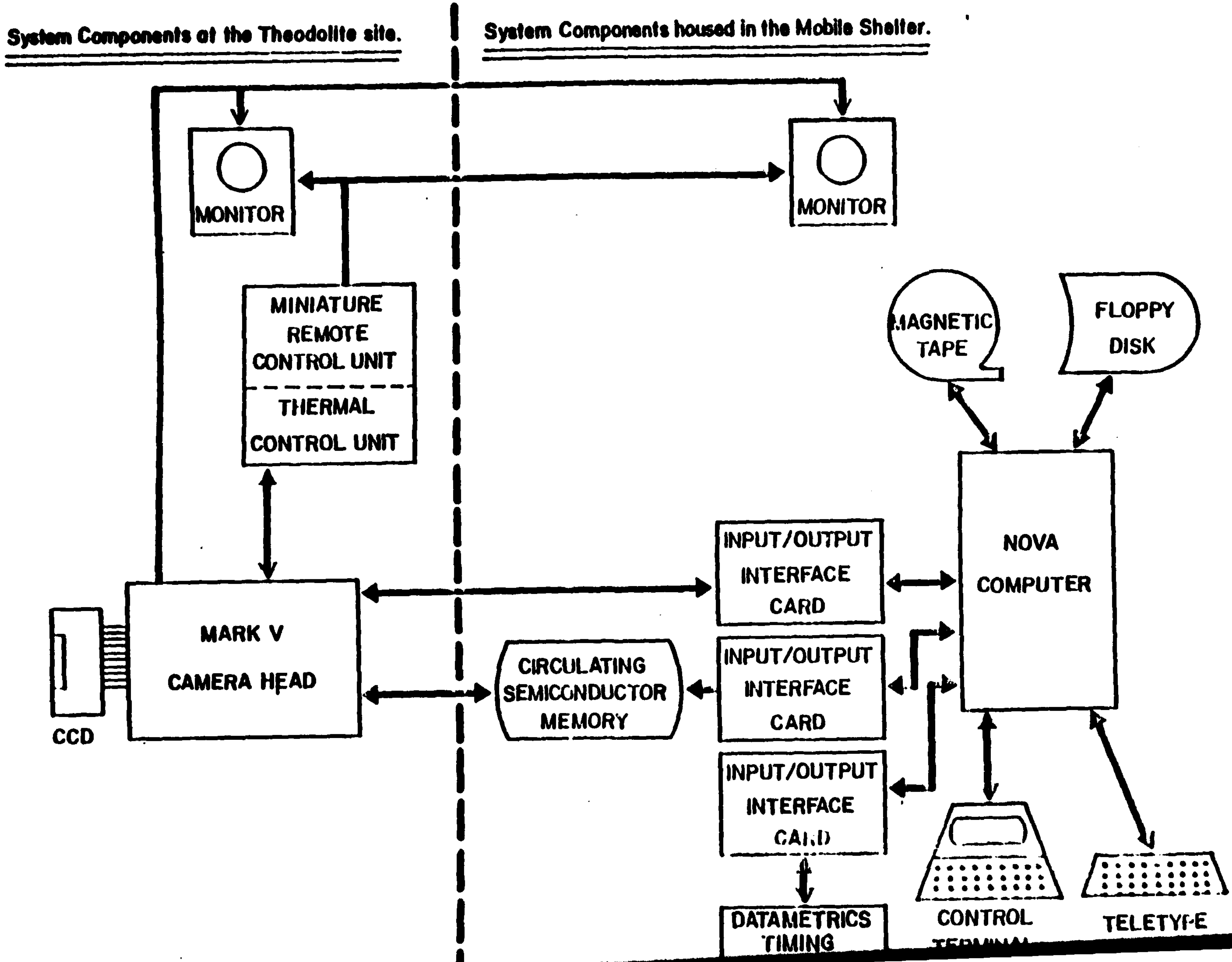
(a) T-4 Astronomic Theodolite (Figure 2) - normal observing procedures are followed with the human eye replaced by the CCD eyepiece.

(b) CCD Eyepiece - detects the starlight which generates a signal that is input to the computer.

(c) Thermal Control Unit - maintains the CCD at a constant temperature.

(d) Circulating Semiconductor Memory - stores the "dark current noise pattern" which is subsequently subtracted from the signal to produce an image free of background noise.

(e) Nova Computer - performs data processing and intelligent system operational control functions.


System Components at the Theodolite site.
System Components housed in the Mobile Shelter.
MONITOR
MONITOR
MINIATURE REMOTE CONTROL UNIT
THERMAL CONTROL UNIT
MAGNETIC TAPE
FLOPPY DISK
NOVA COMPUTER
INPUT/OUTPUT INTERFACE CARD
INPUT/OUTPUT INTERFACE CARD
INPUT/OUTPUT INTERFACE CARD
MARK V CAMERA HEAD
CCD
CIRCULATING SEMICONDUCTOR MEMORY
DATAMETRICS TIMING
CONTROL
TELETYPE

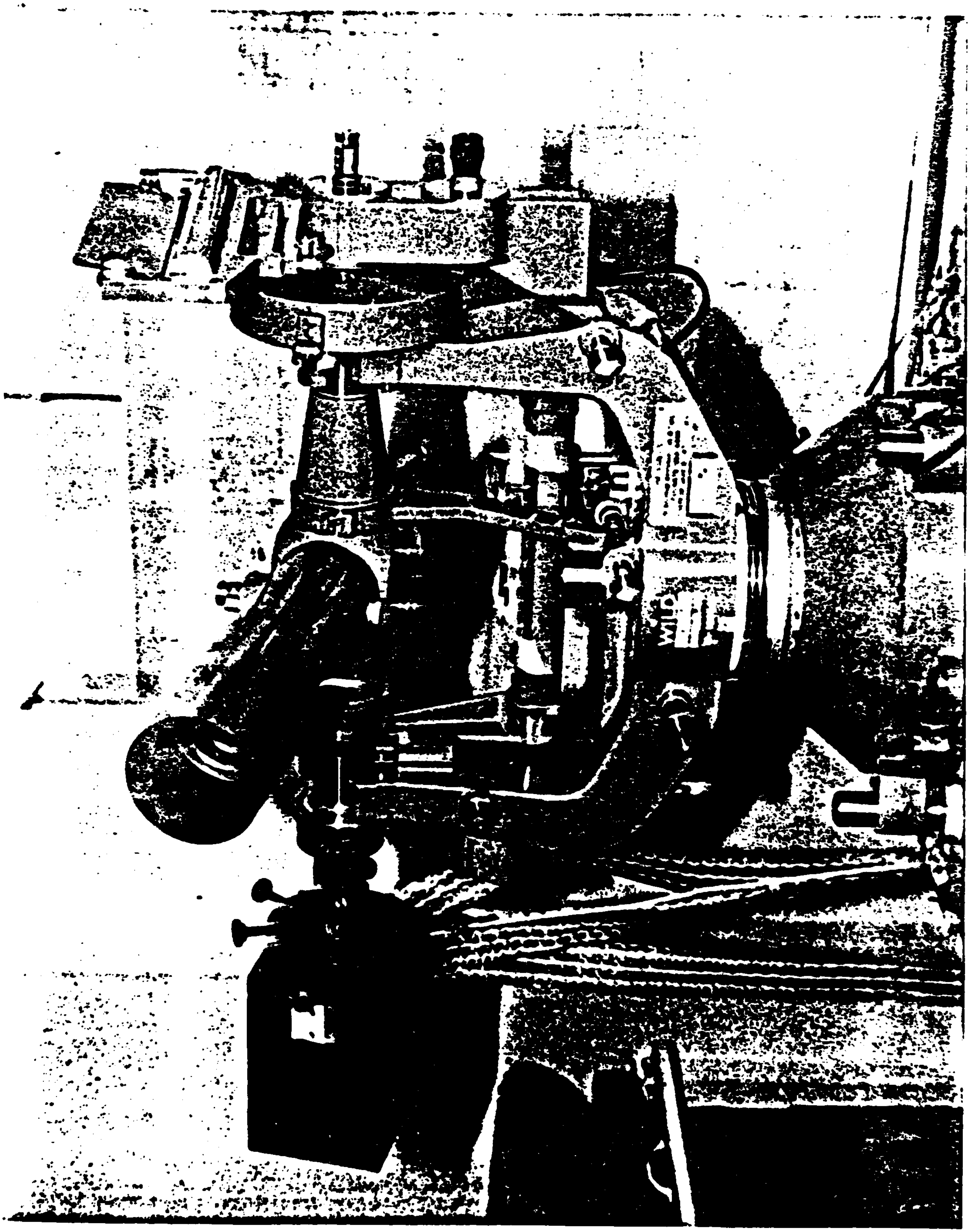


Figure 2

(f) Remote Control Unit - consists of a microprocessor which generates the scanning function and the selection of clock voltages and other operational modes.

(g) Video Amplifiers (Monitors) - provide the observer and the remote system operator with a display of the star image as sensed by the CCD.

(h) Datametrics Timing System - provides time of the astronomic events.

(i) Magnetic Tape Drive - stores programs for input to the Nova computer and stores CCD data for final data reduction.

(j) Control Terminal - input/output device for operational control of the CCD system.

(2) Feasibility and Field Testing. Integration of the DMA prototype CCD system hardware was completed in November 1981. For the next 6 months, during feasibility testing at Beltsville, Maryland, the software was refined for longitude and latitude observations. This testing was done by a composite team of University of Maryland and DMA astronomic observers under the direction of Dr. Douglas Currie, the principal investigator from the University. In May 1982, the CCD system was installed in a mobile shelter and moved to the U.S. Naval Observatory (USNO) Timing Station in Washington, D.C., to begin three weeks of operational testing and evaluation by DMAHTC/GSS astronomic observers. A summary of astronomic longitudes determined using the CCD is given in Table 4. The close agreement (-0.05 arc second) and the small standard error of a single night ($\pm$.11 arc second secant ϕ) were particularly gratifying.

In June 1982, the system was moved to Cheyenne, Wyoming, where it was tested for seven weeks. During this test, there was one hardware failure in the power supply that was repaired. The second failure on 16 August caused a delay of over two months, as several attempts were made to repair the system before the problem was determined to be in the Nova computer. In early December 1982, testing was resumed.

The result of the CCD system's longitude determination compared to the standard station at Cheyenne was +0.07 arc second. However, the standard error of a single night was $\pm$0.29 arc second secant ϕ, or three times that obtained at the USNO station in Washington, D.C. (Table 5).

These preliminary results from testing the prototype system have encouraged DMA to contract for two production models of the CCD system during fiscal year 1983. Testing and evaluation of the prototype system will continue at standard reference stations at the White Sands Test Range in New Mexico, and the USNO Timing Substation in Flagstaff, Arizona. The system will then be sent back to the USNO Timing Station in Washington, D.C. for further testing.

Table 4

CCD FINAL ASTRONOMIC LONGITUDE RESULTS
AT STATION DANJON ASTRO (USNO), WASHINGTON, D.C.

1982 LOCAL DATE	ASTRONOMIC LONGITUDE FOR NIGHT	RESIDUAL FROM STANDARD	NUMBER OF SETS
	DEG MIN SEC	SECONDS	
29 April	77°03'58"04	-0"19	2
3 May	58.12	-0.11	4
4 May	58.42	+0.19	4
5 May	58.10	-0.13	5
6 May	58.21	-0.02	5
10 May	58.32	+0.09	4
11 May	58.01	-0.22	3
13 May	58.39	+0.16	2
25 May	58.25	+0.02	4
26 May	58.25	+0.02	5
1 June	58.12	-0.11	5
2 June	58.13	-0.10	3
7 June	57.96	-0.27	3
8 June	58.12	-0.11	2
			51 SETS

WEIGHTED MEAN	58"18	±0"036	(350 STARS OBSERVED)
FIXED POSITION	58"23	±0"009	(OVER 50,000 STARS OBSERVED)
DIFFERENCE	-0"05		

STANDARD ERROR OF A SINGLE NIGHT ±0"11 secant ϕ

Table 5

5 Nov 1982

ASTRONOMIC LATITUDE COMPARISON AT F. E. WARREN AFB, WY

Type of Instrument	Wild T-4 Theodolite With CCD Eyepiece	Danjon* Astrolabe	WILD T-4 W/Micrometer[2]
Weighted Mean	58".52	58".24	58".32
Residual from Standard	0".20 N	0".08 S	-
Standard Error of Mean	±0".43	±0".010	±0".016
Std Deviation of a Single Set	±1".13	±0".128	±0".296
Number of Sets	7	51	338
Number of Stars Accepted	48	1050	2700
Date of Observations	Jul, Aug 1982	Aug, Sep 1982	Aug-Nov 1977

ASTRONOMIC LONGITUDE COMPARISON AT F. E. WARREN AFB, WY

Type of Instrument	Wild T-4 Theodolite With CCD Eyepiece	Danjon Astrolabe	WILD T-4 W/Micrometer
Weighted Mean	47".32	47".11	47".25
Residual from Standard	0".07 W	0".14 E	-
Standard Error of Mean	±0".079	±0".019	±0".068
Std Deviation of a Single Set	±0".635	±0".135	±1".223
Number of Sets	64	51	322
Number of Stars Accepted	431	302	2600
Date of Observations	Jun-Aug 1982	Aug, Sep 1982	Aug-Nov 1977

STANDARD POSITION OF STATION: 41°07'58".32 N 104°51'47".25 W

[2] Gilbert, 1979, p.31

*Preliminary Results

Although the CCD eyepiece test and evaluation are not yet complete, the prototype system has demonstrated that it is within state-of-the-art technology to automate astronomic position observations with accuracies equal to, or greater than those obtained by any conventional astronomic instrument.

3. Between-Night Error. Between-night error, other than that attributed to temperature gradients in level vials and other internal stresses in the instrument previously mentioned (and inseparable from instrumental errors), is principally caused by anomalous refraction.

Two-Color Refractometer.

DMA has an R&D program to develop a two-color refractometer system with the objective of measuring total and anomalous refraction for correcting astronomic observations.

The concept is based on the principle that the dispersion, or separation of light into its component wavelengths, which occurs as light from a star passes through the atmosphere, is a function of the index of refraction. By measuring the dispersion angle between the red and blue components of a stellar image, the instantaneous magnitude of refraction can be computed. Using the local temperature, barometric pressure, and humidity, the normal angle of refraction can be computed. The difference between the normal angle of refraction and the value obtained for the instantaneous angle of refraction is the anomalous refraction (Currie, 1977).

A prototype two-color refractometer is scheduled to be tested with a CCD system by DMAHTC/GSS field personnel in late 1982.

DISTANCE MEASUREMENTS

The need for more precision and accuracy in distance measurements also became a problem for DMA surveyors in the early 1970's. While the Geodimeter, Geodolite, and Mekometer improved precision, and consistently provided accuracies approaching one part per million (under good atmospheric conditions), the problem of the uncertainty in the correction for the index of refraction which could be as much as one part per million or even greater, still remained.

In certain applications, such as precise traverses for linking radar systems, precise distance measurements for the orientation of radar arrays at test ranges, and length measurements of the high speed sled test track used to test aircraft and space vehicle aerodynamics, there is a need for accuracies better than one part per million. For these highly accurate measurements, DMA became interested in the multiwavelength distance-measuring instrument (MWDMI), a prototype device built and operated by the Applied Physics Laboratory at the University of Washington, in Seattle, Washington.

The prototype, employing a red helium-neon and a blue helium-cadmium laser, and a microwave frequency, has been used to detect crustal movement across the San Andreas fault zone in Hollister, California since 1974 by the University of Washington personnel under a U.S. Geological Survey (USGS) contract. The dispersive characteristics of air in the visible region of the spectrum cause the two optical signals to travel at slightly different

velocities, from which the average group index of refraction in dry air can be computed. The index of refraction in the microwave region of the spectrum is about 100 times more sensitive to water vapor than the optical index. So, by adding the microwave frequency, the average water vapor content along the path being measured can be evaluated. A small microprocessor controls the instrument and computes the applicable corrections in real time (Huggett and Slater, 1975).

Almost all of the early uses of the MWDMI were for the detection of crustal movement, where the main concern was for measurement of incremental changes in the length of lines to a high degree of accuracy. Field measurements at Hollister, California generally indicated standard errors better than one part in 10^7 on lines of 5 to 10 kilometers (Huggett and Slater, 1975).

In 1978, DMA negotiated with Terra Technology in Seattle, Washington to build a field-portable, multiwavelength distance-measuring device (Terrameter), which would meet the performance specifications of the prototype MWDMI. This instrument would be used for measuring absolute distances, particularly along the 16-kilometer high speed sled test track (HSSTT) in New Mexico.

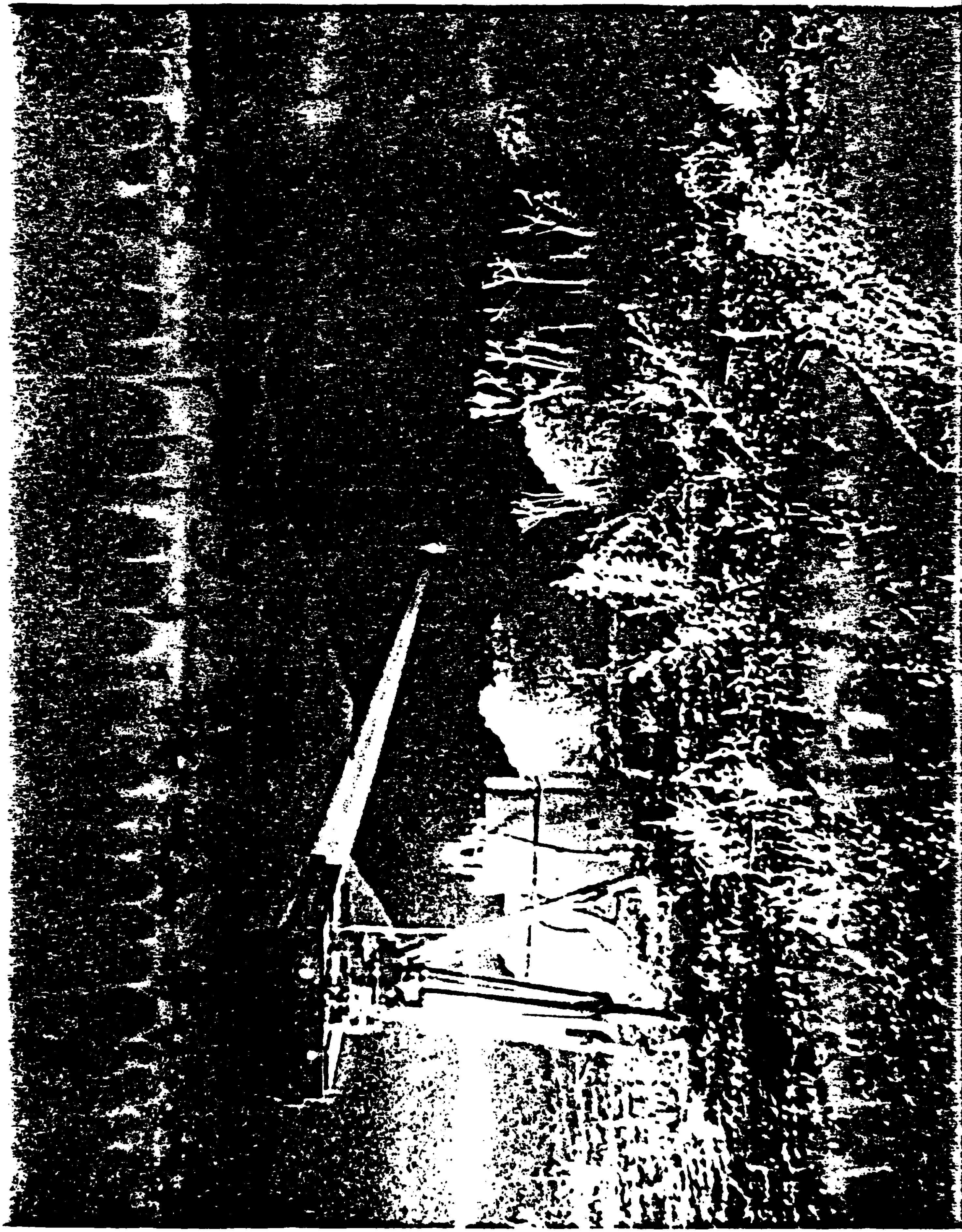
Although the technology was available in the prototype instrument, the contractor's task involved developing, manufacturing, and packaging a relatively small, portable field instrument which would duplicate the functions and performance of the rack-mounted series of components of the prototype MWDMI, that was continuously used at Hollister. The size and configuration of the prototype components filled a medium-sized camper. This formidable problem required extensive development to miniaturize the system's components into state-of-the-art modules that would fit into a portable instrument of reasonable size. For example, it took several months to obtain a phase-locked loop oscillator, which would meet performance specifications. This is the heart of the microwave unit, where the 3.005 gigaherz modulation frequency (derived from a 5 megaherz rubidium frequency standard by an offset RF phase-locked oscillator) is monitored constantly. Other difficulties were encountered with output power, reliability of the blue laser, spurious light (backscatter), overheating of frequency modulator, and high frequency contamination.

The first Terrameter was tested and accepted by the USGS in July 1981 in Pear Blossom, California. The USGS tests were not concerned with absolute length, but rather with incremental changes in lengths of lines radiating from a station which monitored earth crustal movement in the area

DMA Acceptance Testing

a. Performance Specifications.

In December 1981, Dr. G. R. Huggett, principal design engineer, delivered the Terrameter (Figure 3) to New Mexico for acceptance testing on the offset baseline along the high speed sled test track. Contract specifications required that the instrument compare with monumented segments of this offset baseline, ranging from 1 to 10 kilometers, within one part per million. It was assumed that the redundant measurements achieved with invar tapes, the Model 8 Geodimeter, MA-100, Mekometer, and Geodolite over a period



of years had established an accuracy of one part per million or better on this baseline; i.e., canceling out the effects of residual atmospheric refraction and instrumental errors. Also, specifications called for precision (repeatability of measurements) within one part in 10 million.

b. Environmental Factors Affecting the Tests.

Electronic distance measurements (EDM) are greatly affected by the topography, climate, and vegetation over the measured area. Unfortunately, the environmental factors of the test area in New Mexico are poor in all categories. The climate is hot, dry, and usually clear. With the sun heating the ground surface throughout the day, steep vertical temperature gradients are created that cause severe turbulence in the air through which the measurements are made. The topography is uniformly flat, so effects on EDM are not alleviated by measuring with greater clearance above the ground from hilltop to hilltop. Likewise, there is no significant vegetation cover or frequency of overcast skies to alleviate the effects of solar radiation. The presence of severe turbulence precludes the making of precise distance measurements except during a 1-2 hour period at dawn and dusk, when the cooling ground surface is temporarily in thermal equilibrium with the air. These turbulent atmospheric conditions do not affect Geodolite measurements to the same extent. The Geodolite is not as sensitive, because it does not have the shorter wavelength resolution which gives the Terrameter the potential of one order of magnitude better accuracy over a single-wavelength instrument. The modulation wavelength of the Geodolite is about 6 meters versus 10 centimeters for the Terrameter. To obtain the desirable wavelength of 10 centimeters, the Terrameter modulation frequency, created by a microwave cavity resonator and continuously monitored by a phase-locked loop for each laser must be 3.005 gigahertz. The problem is that excessive turbulence causes the instrument to "lose lock" while attempting to measure. When this happens, accurate determinations of distance cannot be made. The solution to this problem is to measure during the times of day, particularly at dusk or dawn or under overcast skies, when atmospheric turbulence is minimal.

c. Test Results.

The severity of the problem of vertical temperature gradients when measuring with the Terrameter was not fully recognized until after a considerable number of measurements had been taken at various times during the day and night over the period of several months. For this reason, much of the data taken during the acceptance tests had to be carefully evaluated with respect to atmospheric conditions as well as the instrument's performance capability. A loose mounting bracket in one retro-reflector also caused some poor measurements and the problem was not discovered until near the end of the testing. Also, all the acceptance test measurements were taken from 6-20 meter towers on the offset baseline. Other measurements were taken on a center-point quadrilateral, designated as the "AITL Quad". These measurements were not part of the contract acceptance tests.

As a result of these early tests, it is now an established procedure that distance measurements with the Terrameter be taken under optimum conditions, generally at dusk, dawn, or on cloudy days. When these conditions are met, a precision of one part in 10^7 usually can be obtained for lengths of 1-10 kilometers. There have been no extensive tests on the maximum range of

this instrument. It is probably capable of measuring up to 15 kilometers under favorable conditions.

The potential accuracy of the Terrameter beyond one part in 10^6 has not been verified empirically. The accuracy of the offset baseline is estimated at one part in 10^6 or better. Precision terms and the fairly universal acceptance of the multiwavelength distance measurement theory and error models tend to substantiate expectations that the accuracy of measurements should approach one part in 10^7 under optimum conditions. Test results are shown in Tables 6 and 7. For reasons mentioned previously, these tests are not conclusive. Further testing must be done to evaluate the accuracy of the instrument. This task is complicated by the unfavorable environmental factors at the New Mexico site.

In future tests, DMA hopes to compare the Terrameter with other distance measuring instruments of comparable accuracy. There is a multiwavelength instrument in the final stages of development at the Joint Institute for Laboratory Astrophysics (JILA) of the National Bureau of Standards and the University of Colorado at Boulder, Colorado. The principal difference between the MWDMI instrument in Boulder and the Terrameter is the replacement of the retro-reflector of the Terrameter system by a second transmitter and an active receiver allowing signals to be transmitted and received at both ends of the line. The advantage of two-way transmissions is chiefly an increased range capability--up to 50 kilometers, in theory at least. The range capability of the Terrameter is limited to about 15 kilometers by the spreading and attenuation of the laser beams, particularly the blue laser. In reality, the limiting range of any MWDMI instrument will be dependent upon atmospheric conditions. The disadvantage of the two-way system is an increase in size and weight of the instrumentation required at each end of the line. It is still readily transportable, however, by vehicle or helicopter (Moody and Levine, 1979). Since MWDMI technology is not presently suitable or required for most routine distance measurements, this is not a significant factor.

Another instrument capable of measuring a comparison baseline for the Terrameter is the Hewlett Packard Model 5526A laser interferometer measuring system (Figure 4). This device has been adapated by Captain Leonard S. Baker (retired, National Geodetic Survey) to measure distances near 25 meters (within ±5 microns) in an ultraprecise traverse network for construction of a particle accelerator at Brookhaven National Laboratory on Long Island, New York. These continued development efforts should result, eventually, in the measurement of distances to one part in 10^7 accuracy under optimum atmospheric and terrain conditions.

RELATIVE AND ABSOLUTE GRAVITY

DMA is responsible for the accomplishment of land, marine, and benthic (underwater) gravity surveys of the U.S. and nearshore areas to support DoD programs. DMA also played an active role in the worldwide gravity surveys necessary for the establishment of the International Gravity Standardization Net of 1971 (IGSN 71).

Table 6

PROJECT: COMPARISON OF GEODOLITE AND TERRAMETER DISTANCES

	TERRAMETER DISTANCES:				GEODOLITE DISTANCES:		
	GEOD DIST	RESID	DATE	SE	GEOD DIST	RESID	DATE
AITL AZ PIER — AITL NW PIER							
	2065.9201	0.7	24 NOV 81	.20	2065.9155	-2.9	01 MAR 79
	2065.9197	0.3	24 NOV 81	.14	2065.9128	-5.6	27 MAR 79
	2065.9199	0.5	03 DEC 81	.17	2065.9212	2.8	04 DEC 79
	2065.9196	0.2	03 DEC 81	.14	2065.9238	5.4	05 DEC 79
	2065.9192	-0.2	04 DEC 81	.15	2065.9160	-2.4	27 APR 81
	2065.9192	-0.2	04 DEC 81	.09	2065.9165	-1.9	27 APR 81
	2065.9203	1.1	20 JAN 82	.39	2065.9211	2.7	28 APR 81
	2065.9195	0.1	20 JAN 82	.22	2065.9202	1.8	28 APR 81
	2065.9192	-0.2	20 JAN 82	.30			
	2065.9192	-0.2	26 JAN 82	.19			
	2065.9186	-0.8	26 JAN 82	.24			
	2065.9181	-1.3	02 FEB 82	.12			
	2065.9183	-1.1	02 FEB 82	.10			
	2065.9204	1.0	05 FEB 82	.54			
	2065.9193	-0.1	08 FEB 82	.39			
	2065.9192	-0.2	08 FEB 82	.39			
MEAN =	2065.9194	1.0			2065.9184		
AITL AZ PIER — AITL N PIER							
	1855.1558	-0.7	24 NOV 81	.54	1855.1540	-2.4	01 MAR 79
	1855.1555	-1.0	24 NOV 81	.38	1855.1560	-0.4	28 MAR 79
	1855.1560	-0.5	03 DEC 81	.09	1855.1582	1.8	04 DEC 79
	1855.1561	-0.4	03 DEC 81	.24	1855.1576	1.2	05 DEC 79
	1855.1563	-0.2	04 DEC 81	.14	1855.1576	1.2	28 APR 81
	1855.1562	-0.3	04 DEC 81	.10	1855.1574	1.0	28 APR 81
	1855.1578	1.3	03 FEB 82	.14	1855.1556	-0.8	28 APR 81
	1855.1575	1.0	03 FEB 82	.13	1855.1552	-1.2	28 APR 81
	1855.1571	0.6	04 FEB 82	.11			
	1855.1570	0.5	09 FEB 82	.10			
MEAN =	1855.1565	0.1			1855.1564		
AITL AZ PIER — AITL W PIER							
	1548.9990	-0.3	24 NOV 81	.20	1549.0002	-1.6	01 MAR 79
	1548.9989	-0.4	24 NOV 81	.20	1549.0030	1.2	26 MAR 79
	1548.9990	-0.3	03 DEC 81	.19	1549.0037	1.9	05 DEC 79
	1548.9992	-0.1	03 DEC 81	.31	1549.0050	3.2	05 DEC 79
	1548.9991	-0.2	04 DEC 81	.28	1548.9991	-2.7	24 APR 81
	1548.9989	-0.4	04 DEC 81	.25	1548.9996	-2.2	24 APR 81
	1548.9986	-0.7	28 JAN 82	.30	1549.0073	5.5 R	28 APR 81
	1548.9986	-0.7	28 JAN 82	.23	1549.0072	5.4 R	28 APR 81
	1549.0001	0.8	01 FEB 82	.38			
	1549.0006	1.3	02 FEB 82	.17			
	1549.0006	1.3	02 FEB 82	.16			
MEAN =	1548.9993	-2.5			1549.0018		
AITL NW PIER — AITL N PIER							
	1452.3214	-0.2	16 NOV 81	.10	1452.3180	-4.4	27 MAR 79
	1452.3214	-0.2	16 NOV 81	.35	1452.3233	0.9	28 MAR 79
	1452.3217	0.1	16 NOV 81	.16	1452.3266	4.2	04 DEC 79
	1452.3214	-0.2	16 NOV 81	.08	1452.3247	2.3	04 DEC 79
	1452.3210	-0.6	02 FEB 82	.08	1452.3200	-2.4	27 APR 81
	1452.3211	-0.5	02 FEB 82	.14	1452.3189	-3.5	27 APR 81
	1452.3222	0.6	03 FEB 82	.15	1452.3240	1.6	28 APR 81
	1452.3224	0.8	03 FEB 82	.14	1452.3233	0.9	28 APR 81
	1452.3229	1.3	08 FEB 82	.77	1452.3224	0.0	16 NOV 81
	1452.3232	1.6	08 FEB 82	.45			
	1452.3224	0.8	09 FEB 82	.52			
	1452.3217	0.1	09 FEB 82	.40			
	1452.3198	-1.8	26 FEB 82	.06			
	1452.3196	-2.0	26 FEB 82	.06			
MEAN =	1452.3216	-0.8			1452.3224		
AITL NW PIER — AITL W PIER							
	1477.4602	0.8	16 NOV 81	.15	1477.4649	5.5 R	26 MAR 79
	1477.4601	0.7	16 NOV 81	.12	1477.4573	-2.1	27 MAR 79
	1477.4602	0.8	16 NOV 81	.10	1477.4661	6.7 R	04 DEC 79
	1477.4593	-0.1	28 JAN 82	.14	1477.4633	3.9	05 DEC 79
	1477.4586	-0.8	28 JAN 82	.17	1477.4584	-1.0	24 APR 81
	1477.4579	-1.5	01 FEB 82	.08	1477.4579	-1.5	24 APR 81
	1477.4581	-1.3	01 FEB 82	.10	1477.4592	-0.2	27 APR 81
	1477.4614	2.0	02 FEB 82	.18	1477.4584	-1.0	27 APR 81
	1477.4588	-0.6	02 FEB 82	.28	1477.4610	1.6	16 NOV 81
	1477.4606	1.2	02 FEB 82	.20			
	1477.4583	-1.1	02 FEB 82	.15			
	1477.4601	0.7	08 FEB 82	.09			
	1477.4596	0.2	08 FEB 82	.15			
	1477.4593	-0.1	26 FEB 82	.08			
	1477.4591	-0.3	26 FEB 82	.10			
MEAN =	1477.4594	0.0			1477.4594		
AITL W PIER — AITL N PIER							
	2387.1575	-1.6	28 JAN 82	.30	2387.1603	3.4	26 MAR 79
	2387.1571	-2.0	28 JAN 82	.34	2387.1586	1.7	28 MAR 79
	2387.1594	0.3	01 FEB 82	.20	2387.1647	7.8 R	04 DEC 79
	2387.1589	-0.2	01 FEB 82	.19	2387.1648	7.9 R	05 DEC 79
	2387.1601	1.0	02 FEB 82	.24	2387.1552	-1.7	24 APR 81
	2387.1607	1.6	02 FEB 82	.26	2387.1543	-2.6	24 APR 81
	2387.1592	0.1	03 FEB 82	.15	2387.1563	-0.6	28 APR 81
	2387.1590	-0.1	03 FEB 82	.10	2387.1567	-0.2	28 APR 81
	2387.1594	0.3	09 FEB 82	.26			
	2387.1589	-0.2	09 FEB 82	.15			
	2387.1597	0.6	26 FEB 82	.15			
	2387.1590	-0.1	26 FEB 82	.10			
MEAN =	2387.1591	2.2			2387.1569		
AITL AZ PIER — AITL NEW							
	3017.6324	-1.5	25 JAN 82	.36	3017.6301	1.1	21 JAN 82
	3017.6327	-1.2	25 JAN 82	.42	3017.6280	-1.0	04 FEB 82
	3017.6336	-0.3	26 JAN 82	.24			
	3017.6329	-1.0	26 JAN 82	.16			
	3017.6359	2.0	05 FEB 82	.31			
	3017.6355	1.6	08 FEB 82	.36			
	3017.6345	0.6	08 FEB 82	.22			
MEAN =	3017.6339	4.9			3017.6290		
AITL NW PIER — AITL NEW							
	951.7083	-1.0	26 JAN 82	.18	951.7119	0.0	21 JAN 82
	951.7098	0.5	26 JAN 82	.20	951.7120	0.1	04 FEB 82
	951.7075	-1.8	02 FEB 82	.21			
	951.7077	-1.6	02 FEB 82	.19			
	951.7110	1.7	05 FEB 82	.28			
	951.7100	0.7	05 FEB 82	.26			
	951.7092	-0.1	05 FEB 82	.25			
	951.7094	0.1	08 FEB 82	.20			
	951.7084	-0.9	08 FEB 82	.16			
	951.7105	1.2	08 FEB 82	.39			
	951.7100	0.7	08 FEB 82	.43			
MEAN =	951.7093	-2.7			951.7120		
AITL N PIER — AITL NEW							
	2089.8319	-0.1	03 FEB 82	.20	2089.8301	-0.1	29 JAN 82
	2089.8316	-0.6	03 FEB 82	.24	2089.8304	0.2	04 FEB 82
	2089.8310	-1.2	05 FEB 82	.25			
	2089.8312	-1.0	08 FEB 82	.39			
	2089.8308	-1.4	08 FEB 82	.08			
	2089.8344	2.2	09 FEB 82	.37			
	2089.8343	2.1	09 FEB 82	.39			
MEAN =	2089.8322	2.0			2089.8302		

Table 7

SUMMARY OF TERRAMETER MEASUREMENTS
(HAFB HIGH SPEED TRACK AND AITL NET)

TERRAMETER MEASUREMENTS SAMPLE SIZE	MEAN (MILLIMETERS)	SIGMA (MILLIMETERS)	COMPARED WITH COMB'D ADJ	GEODO-LITE	INVAR WIRE	HAFB HIGH SPEED TRACK AND AITL NET MEASUREMENT ENDPOINTS	
2	#384,268.9	1.0	-3.3	-3.0	-4.4	IC-0 OFFSET	IC-2 OFFSET
8	729,316.8	2.0	+0.4	+1.7	-1.2	IC-13 OFFSET	IC-14 OFFSET
4	792,320.2	0.3	-1.1	-2.5	-3.1	IC-4 OFFSET	IC-5 OFFSET
4	792,324.3	1.3	-2.3	-2.6	-3.1	IC-9 OFFSET	IC-10 OFFSET
3	792,324.7	1.3	-0.8	-1.4	-2.0	IC-5 OFFSET	IC-6 OFFSET
6	792,335.5	1.5	-1.9	-4.7	-1.0	IC-12 OFFSET	IC-13 OFFSET
11	**** 951,709.3	1.2	** -0.9	** -2.5	**********	AITL NW PIER	AITL NEW
3	1,176,606.0	2.0	-1.2	-1.7	-2.0	IC-0 OFFSET	IC-3 OFFSET
14	** 1,452,321.6	1.0	** -0.8	** -0.7	**********	AITL NW PIER	AITL N PIER
15	** 1,477,459.4	1.0	** -1.2	** -0.6	**********	AITL NW PIER	AITL W PIER
11	** 1,548,999.3	0.7	** -2.2	** -3.9	**********	AITL AZ PIER	AITL W PIER
5	1,584,649.9	2.7	+0.4	+1.0	+0.1	IC-4 OFFSET	IC-6 OFFSET
4	1,584,653.0	1.1	-0.5	-1.0	+2.2	IC-8 OFFSET	IC-10 OFFSET
6	1,584,655.0	2.1	-0.5	+1.4	+0.5	IC-12 OFFSET	IC-14 OFFSET
10	** 1,855,156.5	0.8	** -0.8	** -0.1	**********	AITL AZ PIER	AITL N PIER
3	1,968,938.1	1.9	-0.4	-0.6	-1.9	IC-0 OFFSET	IC-4 OFFSET
16	** 2,065,919.4	0.7	** +0.7	** +1.3	**********	AITL AZ PIER	AITL NW PIER
7	** 2,089,832.2	1.5	** +0.6	** +1.6	**********	AITL N PIER	AITL NEW
4	2,376,973.6	0.8	+0.4	+1.0	+4.1	IC-7 OFFSET	IC-10 OFFSET
12	** 2,387,159.1	1.0	** +2.0	** +0.6	**********	AITL W PIER	AITL N PIER
4	2,761,265.0	1.0	+2.1	+3.6	+1.7	IC-0 OFFSET	IC-5 OFFSET
7	** 3,017,633.9	1.4	** +4.9	** +4.0	**********	AITL AZ PIER	AITL NEW
4	3,169,297.9	1.6	+0.8	+1.5	+3.3	IC-6 OFFSET	IC-10 OFFSET
3	3,553,591.0	0.7	+2.3	+3.6	+1.0	IC-0 OFFSET	IC-6 OFFSET
4	3,961,623.7	0.5	+0.7	+1.2	+2.4	IC-5 OFFSET	IC-10 OFFSET
4	4,345,913.3	1.4	+1.3	+2.7	-1.8	IC-0 OFFSET	IC-7 OFFSET
3	4,753,946.2	1.2	+0.5	+1.0	+1.6	IC-4 OFFSET	IC-10 OFFSET
4	5,138,229.5	1.1	-0.1	+0.3	-4.3	IC-0 OFFSET	IC-8 OFFSET
3	5,546,277.3	0.9	+0.9	+1.8	+0.7	IC-3 OFFSET	IC-10 OFFSET
4	5,930,560.6	1.9	+2.3	+3.7	+3.4	IC-0 OFFSET	IC-9 OFFSET
4	6,338,613.3	1.0	+0.8	+1.3	+2.0	IC-2 OFFSET	IC-10 OFFSET
3	6,655,539.4	0.9	+2.6	+4.4		IC-1 OFFSET	IC-10 OFFSET
7	6,722,887.6	1.6	+1.5	+3.8	+3.0	IC-0 OFFSET	IC-10 OFFSET
2	8,715,582.8	2.6	+2.5	+5.1		IC-10 OFFSET	IC-22 OFFSET

The TERRAMETER was not developed with the intention of measuring lines of less than 500 meters

* The asterisked lines are AITL net (quad) measurements

Figure 4

The need for increased accuracies in relative and absolute gravity measurements in the last decade prompted DMA to cooperate with the National Geodetic Survey (NGS) in 1978 to establish the U.S. Interagency Gravity Standards Committee (USIGSC) in order to address the problem on a national scale. Members of the USIGSC are from the National Geodetic Survey, U.S. Geological Survey, Air Force Geophysics Laboratory, DMA Aerospace Center, DMA Hydrographic/Topographic Center, Ohio State University, and the Joint Institute for Laboratory Astrophysics. Some of the principal objectives of this interagency committee have been to improve the U.S. Gravity Base Network, support the development and improvement of absolute gravity instruments, establish absolute calibration lines, publish land gravity survey standards and relative gravity survey specifications, and participate in international gravity measurements to improve the IGSN 71 datum.

1. U.S. Gravity Base Network

a. Primary Absolute Stations. The U.S. Gravity Base Network will be based on 12 primary absolute stations located on tectonically stable bedrock areas, wherever possible. Approximately 20 secondary absolute stations will also be established. From this national network of absolute stations, first order relative base station surveys will be made to provide the framework for regional gravity (anomaly) surveys of a much higher density (Figure 5).

b. Absolute Gravity Calibration Lines. The Mid-Continental Calibration Line (MCCL) has been established (Figure 5) with a range of 1677 milligals. Between 1977 and 1982, absolute gravity measurements have been made with three different absolute gravity devices. Also, observations have been made over the entire line about six times using four LaCoste & Romberg relative gravimeters each trip. The merging of both relative and absolute gravity data provides the means of analyzing systematic errors in these measurements, and tables for dial factors and scale of the relative gravimeters. These periodic measurements will continue. There are plans to establish an Eastern Absolute Gravity Calibration Line under the auspices of the Interagency Gravity Standards Committee in the near future. In addition, short range calibration lines (with 200 to 300 milligal range) will be established for the investigative analysis of the LaCoste & Romberg gravimeter circular error.

2. Absolute Gravity Measurements

In 1980, DMA provided support for absolute gravity measurements on the U.S. Gravity Base Network performed by the Air Force Geophysics Laboratory and the Istituto di Metrologia "G. Colonnetti" of Torino, Italy.

In the spring of 1982, DMAHTC/GSS provided logistical support for an extensive field test of an improved free-falling absolute gravity device, using stabilized laser interferometric techniques, developed at the Joint Institute for Laboratory Astrophysics (JILA) of the National Bureau of Standards and the University of Colorado in Boulder, Colorado. Over a period of 2 months, this device was transported by vehicle from Boulder to six sites in California, three sites on the Mid-Continental Calibration Line (New Mexico, Wyoming, and Montana), the National Bureau of Standards site in Gaithersburg, Maryland, and the Air Force Geophysics Laboratory near Boston, Massachusetts. The location of the sites is shown in Figure 6. The results of these measurements, compared with previous observations where sites were

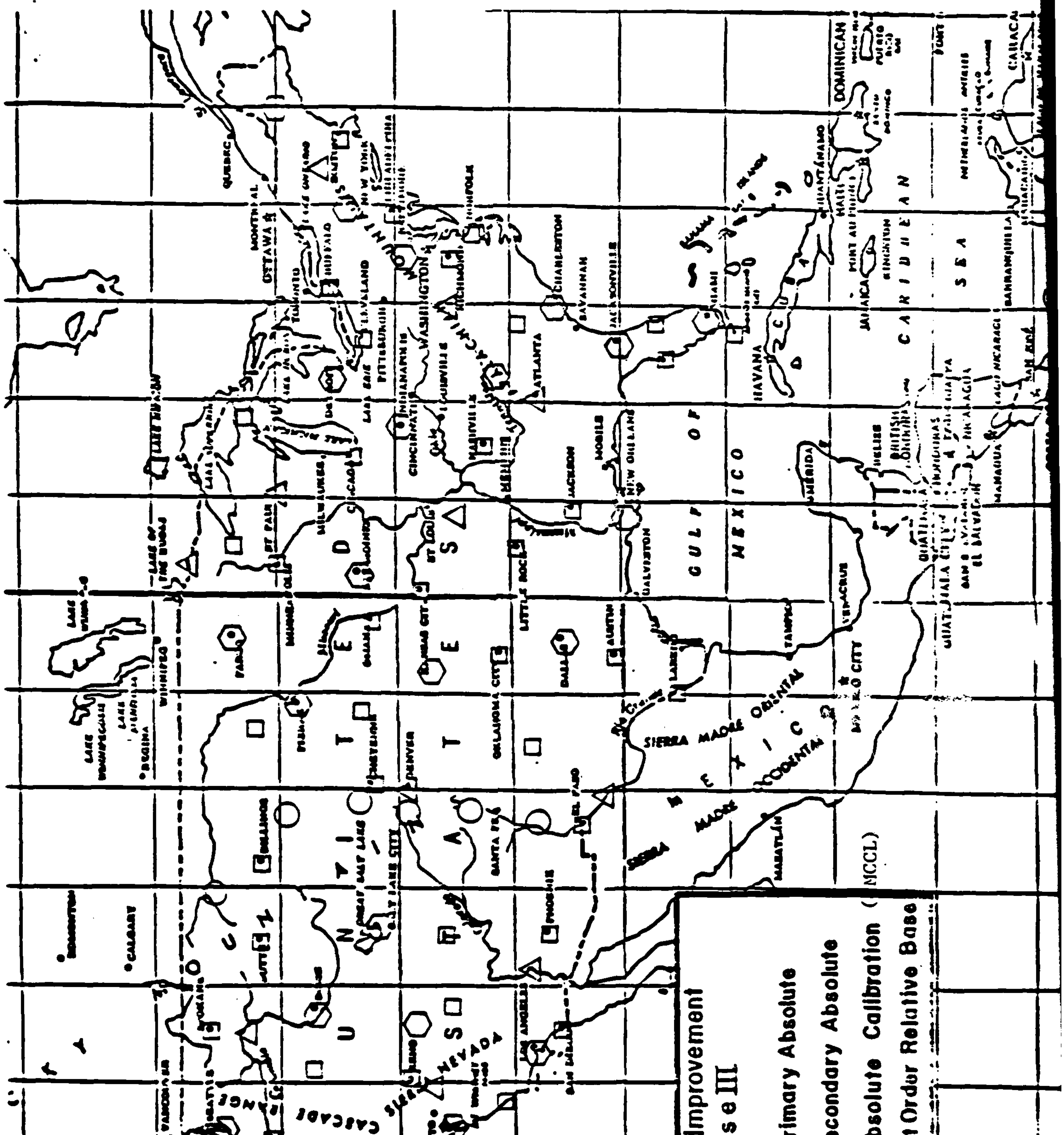
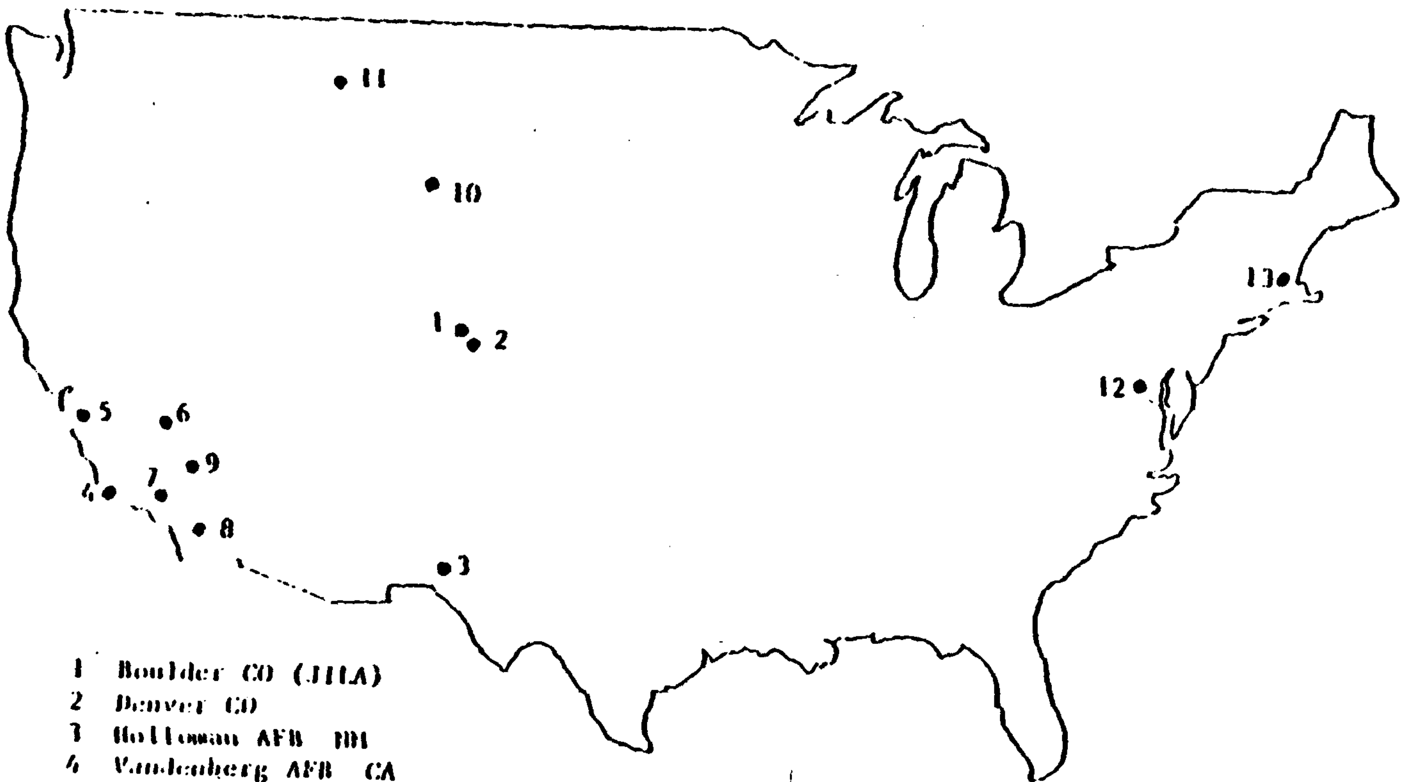

U.S. Gravity Improvement
Phase III
Legend:
Primary Absolute
Secondary Absolute
Absolute Calibration (MCCL)
1st Order Relative Base
GULF OF MEXICO
CARIBBEAN SEA
UNITED STATES
MEXICO
SIERRA MADRE ORIENTAL
SIERRA MADRE OCCIDENTAL
CASCADE RANGE
SIERRA NEVADA

Figure 5



1 Boulder CO (JILA)
2 Denver CO
3 Holloman AFB NM
4 Vandenberg AFB CA
5 Lick Observatory CA
6 Owens Valley Observatory CA
7 Pasadena CA (Kresge Lab)
8 Pinyon Flat Observatory CA
9 Goldstone Observatory CA
10 Sheridan WY
11 Great Falls MT
12 Gaithersburg MD (NBS)
13 Hanscom AFB MA (AFGL)

Figure 6

collocated are shown in Table 8. A detailed account of this survey will be published in the Journal of Geophysical Research (Zumberge, Faller, and Gschwind, 1983).

The JILA absolute gravity meter has significantly reduced the time for a complete set of measurements. The instrument's reduced size makes it much more transportable and easier to set up than previous absolute gravity devices (see Figure 7). The average time to complete a set of measurements at a site, including set-up and tear-down is 6-8 hours.

Dr. J. E. Faller is continuing his work at JILA to improve the absolute gravity device. It is expected that these improvements will further enhance the ease of operation and portability of the instrument, reduce the time required at a site, and increase the accuracy of absolute gravity measurements.

3. Relative Gravity Measurements

There have been a number of improvements in the methodology of relative gravity anomaly surveys which will be mentioned briefly:

a. Inertial Positioning Systems (IPS). Although the IPS is capable of reading gravity gradients with increasing accuracy in a vehicle or landed helicopter, the system is primarily used by DMA to provide low-order geodetic control for regional gravity stations established with the LaCoste & Romberg land gravimeter. The inertial positioning system mounted in a helicopter can provide high productivity, especially in remote, mountainous terrain.

b. Helicopter Sling Gravimeter. Using a modified LaCoste & Romberg underwater gravimeter, DMA field personnel and personnel from Carson Helicopters, Inc. performed tests which involved hovering in a helicopter over a station where the gravimeter is lowered to the ground, leveled, and read by remote control. These tests have been unsuccessful due to the difficulty in obtaining a zero velocity update for the vertical channel in a helicopter hover mode. Horizontal coordinates do not present a problem. In areas where map-identifiable elevations are sufficient in accuracy, this method should be feasible and particularly useful for gravity surveys of inaccessible land areas or shallow lakes and marshes. The problem of dynamic vertical positioning should soon be solved with Global Positioning System technology or refinement of the inertial positioning system.

c. Airborne Gravity Sytems.

After more than 10 years of research to develop an airborne gravity measuring system, in both fixed-wing aircraft and helicopters, tests of the Airborne Gravity Profiling System developed by Carson Helicopters, Geoscience Division in Perkasie, Pennsylvania, indicate success. The Carson system uses the LaCoste & Romberg stable-platform Air/Sea Gravity Meter installed in a Sikorsky S-61 helicopter. Positioning is provided by a Motorola range-range navigation system and elevations above the ground surface by radar altimetry.

In a test performed for DMA in 1982 over the Pamlico Sound area of North Carolina, missions were flown at night at an altitude of 525 meters and speed of 50 knots. Flight lines were spaced 8 kilometers with cross

Table 8

Intercomparison results of absolute gravity measurements.

	JILA		AFG		IMGC	
	1981	1982	1979	1980	1977	19
Holloman AFB	result (gal) date gradient $g-\bar{g}$ h=1 m	979. 139 615 21 March 2.99 +12	979. 139 600 6 July 2.85 +11	979. 139 600 14&31 May 2.85 +11		979. 13 2-3 Ju 3.14 -34
Vandenberg AFB		979. 627 138 26 March 3.44 -38		979. 628 190 3-4 June 3.21 +38		
Lick Obs.		979. 635 503 27 March 4.42 -13		979. 635 503 6-8 June 4.15 +13		
JILA	979. 608 568 Apr.-Dec. 2.39 +10	979. 608 565 Feb.-Apr. 2.39 +6		979. 608 585 18-23 Oct. 2.28 +38		979. 60 26-27 M 2.32 -54
Sheridan		980. 208 952 16 April 2.58 -17	980. 208 912 18-19 July 2.32 -31	980. 208 964 13-16 Oct. 2.44 +9		980. 20 12-14 J 2.56 +40
NBS		980. 103 259 28-29 April 3.25 +1		980. 103 257 13-14 March 3.25 -1		
AFGL		980. 378 697 1 May 3.07 +17	980. 378 685 2 yr. ave. 2.97 +5	980. 378 685 1 yr. ave. 2.97 +5	980. 378 659 Oct. & Dec. 3.02 -26	
Denver	979. 598 322 16-17 Dec. 2.92 +30	979. 598 302 1 Mar. 2.92 +10	979.598 277 27-29 Apr. 2.92 -15		979. 598 268 16-19 Oct. 2.94 -25	

Figure 7

flights spaced 6.5 kilometers. Although the results of these tests have not be published, preliminary evaluation indicates accuracy ~~between~~ better than 2 milligals compared to ground truth.

d. Gradiometry.

DMA has been active in advancing moving base gradiometry research and development. Recently, specifications have been written and negotiations initiated by DMA, through the Air Force Geophysics Laboratory, to execute a contract for a helicopter gradiometry system which would probably be delivered for testing and evaluation within 2 years.

SUMMARY

The forecast for timely development of geodetic and geophysical instruments to meet the Defense Mapping Agency survey requirements for the remainder of the 1980's and the early 1990's is favorable. While further research and development tests of existing prototype systems are necessary to bring new production model instruments on line, and continually upgrade present methodology, there are no major technological breakthroughs necessary to meet foreseeable accuracy requirements. It is probable that advances in silicon chips, or similar technologies, will provide the major influence on future instrument developments. Field instruments that are easily portable and maintainable will be further miniaturized to function as microprocessor-controlled survey systems in the collection and simultaneous reduction of geodetic and geophysical data.

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